Differences in Vegetation Indices for Simulated Landsat-5 MSS and TM, NOAA-9 AVHRR, and SPOT-1 Sensor Systems

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The objective of this study was to evaluate the effects of the different wavelength bands of the Landsat-5 MSS and TM, NOAA-9 AVHRR, and SPOT-1 sensors on two vegetation indices, the normalized difference (ND) and near IR to red ratio (RATIO). The study also demonstrates how vegetation indices for the Landsat-5 MSS and TM, and SPOT-1 systems may be estimated with NOAA-9 AVHRR data. Agronomic and spectral reflectance measurements of corn (*Zea mays* L.) canopies were acquired with an Exotech 20C spectroradiometer in field experiments at Purdue University (W. Lafayette, IN). The reflectance factor data were averaged into 10 nm bands over the 400–2400 nm wavelength interval. Each experiment included four rates of nitrogen fertilization (0, 67, 134, and 202 kg/ha) and three replicates. The vegetation indices were computed i) for ground-based sensors by integrating the reflectance factor data over the visible and near-IR bands of the four sensors and ii) for simulated satellite-based sensors by modifying the reflectance factors with the filter response of each sensor, atmospheric transmittance, and solar irradiance at the Earth's surface in each 10 nm waveband. Variability in the RATIO between the four sensor systems was greatest during mid-season when maximum amounts of green vegetation were present. Variability in ND for the four sensors was considerably less than for the RATIO and nearly constant for most of the growing season. Comparisons of predicted agronomic variables indicated that AVHRR data can estimate both of the vegetation indices of the MSS, and subsequently, agronomic variables as effectively as direct use of the vegetation indices of the MSS. The vegetation indices of all four systems were associated with similar amounts of variation in the examined agronomic variables. Thus, under similar viewing conditions, the AVHRR may complement measurements of the other sensor systems for monitoring surface features of the Earth. Studies are encouraged that address the effects of the dissimilar viewing conditions (orbital characteristics, spatial resolution, off nadir views, etc.) of these sensor systems on their respective vegetation indices.

Introduction

The use of satellites to monitor land surface features has increased with the near daily coverage of most earth locations by the NOAA series of satellites. The advanced very high resolution radiometer (AVHRR) on the NOAA series of satellites provides a nadir pixel resolution of 1.1 km (Kidwell, 1985). While this resolution is not as fine as that of the Landsat multispectral scanner (MSS) or thematic mapper (TM), or the Systeme Probatoire d'Observation de la Terre (SPOT) sensors, its near daily coverage has made the AVHRR system quite useful to the research community (e.g., Justice, 1986).

Individuals interested in land surface features, in particular, have utilized the visible and near-IR bands of the AVHRR to compute the ratio of the two wave-

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bands [Eq. 1] or a normalized difference (ND) vegetation index [Eq. 2],

$$\text{RATIO} = \text{near IR}/\text{visible}, \quad (1)$$

$$\text{ND} = \text{near IR} - \text{visible}/\text{near IR} + \text{visible}. \quad (2)$$

Ground-based field experiments have found that several agriculturally important variables are related to the RATIO, ND, and other combinations of two or more wavebands in the visible and near IR. Agronomic variables related to these vegetation indices include leaf area index (Asrar et al., 1984; Daughtry et al., 1983; Dusek et al., 1985; Gardner et al., 1985; Hatfield et al., 1985; Hinzman et al., 1986), the photosynthetically active radiation absorbed by a crop canopy (Asrar et al., 1984; Gallo et al., 1985, Hatfield et al., 1984), and wet and/or dry photomass (Dusek et al., 1985; Gardner et al., 1985; Hinzman et al., 1986).

Weekly, or longer, composites of satellite derived ND (Tarpley et al., 1984) have been used to classify land cover types (Tucker et al., 1985), monitor seasonal fluctuations in the extent of vegetation (Goward et al. 1985; Justice et al., 1985; Schneider et al., 1985), and monitor monthly variations in globally averaged atmospheric CO_2 (Tucker et al., 1986). When the daily ND values are composited over a week or more, and the largest daily value retained, the resulting value is usually from a cloud free, near nadir observation (Tarpley et al., 1984; Holben, 1986).

The relationships between agronomic variables and vegetation indices developed in ground-based field experiments have used data primarily from visible and near-IR wavebands analogous to those on the Landsat TM or MSS sensors. However, the vegetation indices that have used AVHRR data were computed with wavebands that differ from those of the TM or MSS systems. Price (1987) has provided calibration coefficients that permit comparisons between data from similar wavebands of different sensor systems. Differences between sensor systems in visible and near-IR wavebands used to compute vegetation indices may be too great, however, to permit direct comparisons. The relationships between vegetation indices that are computed with the various sensor systems, and their different visible and near-IR wavebands, are important to any effort to use multiple sensor systems to monitor global land surface features.

There are numerous differences between the satellite-based sensor systems in addition to their waveband differences. These additional differences are primarily due to differing orbital characteristics and spatial resolution. Several of the effects of off-nadir views on the red and near-IR wavebands have been addressed (Holben and Fraser, 1984; Holben et al., 1986). Atmospheric conditions may also introduce additional variability in the vegetation indices computed with data from different sensors (Jackson et al., 1983). These differences between the selected sensor systems were not directly addressed in this study.

The overall objective of this study was to evaluate the effects of waveband selection on vegetation indices computed from ground-based and simulated satellite observations. This study was an initial step to determine the relationships between the vegetation indices computed from the wavebands included on a current NOAA satellite and those computed from the wavebands of the Landsat MSS and TM and SPOT systems. If the vegetation indices for the various sensors are highly related, then the advances made with one sensor system may be extended and applied to the other sensor systems.

Materials and Methods

Corn (*Zea mays* L.) canopy reflectance and agronomic data for this study were obtained in field experiments conducted at the Purdue University Agronomy Farm, West Lafayette, IN, during the 1978 and 1979 growing seasons. Walburg et al. (1982) provide a complete description of the experimental design. Briefly, corn hybrid 'Beck 65X' was planted on 31 May 1978 at a population of 54,000 plants/ha and 'Pioneer 3183' was planted in 10 May 1979 at 66,000 plants/ha. Four different levels (0, 67, 134, and 202 kg N/ha) of nitrogen fertilizer were applied to the plots of corn that comprised the experiment.

Spectral data collection

Spectral bidirectional reflectance from 400 to 2400 nm was measured with an Exotech 20C spectroradiometer (Leamer et al., 1973) mounted on the boom of a mobile tower at an altitude of 9.1 m above the ground. The spectroradiometer is a circular-variable-filter instrument that measures reflectance at all wavelengths from 400 to 2400 nm as filters are rotated through the optical path of the instrument. With a 15° field of view the instrument viewed a 2.3 m diameter area at the soil surface. Measurements were acquired on 11 dates during 1978 and 12 dates during 1979 on cloudless or near cloudless days when solar elevation angles were greater than 45° and prior to solar noon. A barium sulfate painted panel was used as a reference surface for determining the reflectance factor (Biehl and Robinson, 1983) of each scene. The spectral data were acquired at a spectral bandwidth of less than 2 nm and averaged over 10 nm bands for these analyses.

Agronomic data collection

Agronomic data were collected at approximately weekly intervals and included stage of crop development (Hanway, 1963), canopy leaf area index (LAI), the percent of crop cover as observed from a nadir view of the canopy, the amount of total fresh and dry biomass, the amount of green leaf biomass, and the total plant water content. The proportion of incident photosynthetically active radiation that was absorbed by the canopy (APAR) was computed from the measured LAI as described by Gallo et al. (1985).

Analysis of data

RATIO and ND vegetation indices were computed from relative surface radiances derived for the four sensor systems with the wavebands most similar to those included in bands one and two of the NOAA-9 AVHRR system (Table 1). The selected bands included 2 and 4 of the MSS, 3 and 4 of the TM, and 2 and 3 of the SPOT system. Relative surface radiances (L) for the corn canopies were computed for the visible and near-IR wavebands of the various sensors over 10-nm waveband intervals as

$$L_i = P_i F_i E_i T_i. \quad (3)$$

Included in the computation of the estimates of the relative surface radiances (L) are the ground-measured reflectance

TABLE 1 Visible and Near-IR Wavebands of the Four Sensor Systems Utilized in Computation of the Ground and Simulated Satellite Vegetation Indices

Satellite System	Band Number	Wavebands (nm) Ground	Wavebands (nm) Satellite
Landsat-5			
MSS	2	600–700	590–720
	4	800–1100	790–1100
TM	3	630–690	600–730
	4	760–900	750–930
NOAA-9			
AVHRR	1	580–680	550–750
	2	720–1100	690–1060
SPOT-1			
HRV-1	2	610–680	600–690
	3	790–890	740–900

factors (P), filter responses (F) of each waveband, relative solar irradiance at the Earth's surface (E), and atmospheric transmittance (T) for each 10 nm waveband (i). Two methods were used to compute the relative surface radiances. The first method, referred to as ground observations of surface radiance, utilizes Eq. (3) with P observed as described and $F_i = E_i = T_i = 1$. This ground observation is computed over the nominal visible and near-IR wavebands of the four sensor systems (Table 1). These wavebands have been utilized in numerous ground-based field studies of crop canopy reflectance due to their similarities to the wavebands on the satellite sensors. The limits of these wavebands, except for NOAA-9, are the approximate wavelengths at which the sensors display a 50% filter response.

The second method of computing the vegetation indices, referred to as the simulated satellite observations, included P as well as values for F, E, and T in Eq. (3) at each 10 nm interval of the selected wavebands. A filter response (F) greater than 1% was required for each 10 nm waveband (i) to be included in the computation of the simulated relative radiance for the visible and near-IR wavebands of the sensors. The 10 nm filter responses (F) utilized in the study were determined for, and centered on, each of the 10 nm intervals of the selected visible and near-IR wavebands of the NOAA-9 AVHRR[1] (AVHRR), SPOT HRVI[2] (SPOT), and Landsat-5[3] MSS (MSS) and TM (TM) sensors. Solar irradiance (E) was computed from a model developed by Justus and Paris (1985) and the atmospheric transmissivity (T) was computed with LOWTRAN 6 (Kneizys et al., 1983). Both models were initialized with cloud-free and rural atmospheric conditions. The utilization of Eq. (3) for the simulated satellite observations provides the sun to earth to satellite path of visible and near-IR radiation at the selected 10 nm intervals. The 10 nm waveband interval was selected for the analysis of this study because a field research data base (Biehl et al., 1984) was readily available at this resolution.

[1] Kidwell (1985).

[2] SPOT Image Corporation, 1897 Preston White Dr., Reston, VA 22091.

[3] Santa Barbara Research Center, 75 Coromar Dr. Goleta, CA 93117.

The ratio [Eq. (1)] and normalized difference [Eq. (2)] were computed for the 2 years of the study for the ground and simulated satellite observations. The variability between the maximum and minimum values, as well as the seasonal variability, was computed for the vegetation indices of the four sensor systems.

Linear relationships between the agronomic variables and vegetation indices computed using the ground and simulated satellite data were developed from the 1978 measurements. Linear relationships between the vegetation indices of the MSS, SPOT, and TM sensor systems and those of the AVHRR were developed with the 1978 data and were tested with 1979 data. Equations developed with 1978 data that related vegetation indices of the MSS, SPOT, and TM systems to those of the AVHRR system were utilized to predict the indices for the various systems for the 1979 ground and simulated satellite observations.

The predicted indices were then inserted into the equations developed from the 1978 data that related to the agronomic variables to the indices. The vegetation indices for the MSS, SPOT, and TM were predicted with the AVHRR indices and were compared to the indices measured in 1979 through an analysis of their respective relationships with the agronomic measurements of 1979.

Results and Discussion

The relative solar irradiance at the Earth's surface and atmospheric transmissivity (simulated for one direction, i.e., applied to reflectance factor data of the crop canopies) included in this study were for rural atmospheric conditions and thus represented optimum conditions for observations from a platform in space (Fig. 1). Maximum relative solar irradiance occurred at approximately 550 nm and gradually decreased with increased wavelength. Transmissivity increased with wavelength with exceptions at the wavebands associated with O_2 and H_2O absorption. The canopy reflectance factors varied as a function of the wavelength through the growing season; however, for any single simulated satellite observations only the limits of the visible and near-IR wavebands and the respective filter responses varied between the sensor systems.

The wavebands (Table 1) of the MSS demonstrate the increase in width of the visible and near-IR wavebands of the simulated satellite observations (based on a 1% filter response), compared to those for the ground observations. The interval for MSS Band 2 increased from 600–700 nm for the ground observations to 590–720 nm for the simulated satellite observations. The width of the wavebands utilized in the computation of vegetation indices usually increased for the simulated satellite observations, compared to ground observations, for the MSS, TM, and SPOT systems. The width of the waveband for Band 2 of the AVHRR sensor, however, decreased, as the filter response is less than 1% beyond 1060 nm (Fig. 2). The often cited 1100 nm wavelength limit for Band 2 of the AVHRR appears to have originated with the TIROS-N satellite, which had a 10% filter response at 1100 nm. Recent AVHRR instruments on NOAA-6–NOAA-10 have a filter response of less than 1% at wavelengths greater than 1060 nm. Data was not available for MSS Band 4 beyond the 1100 nm wavelength.

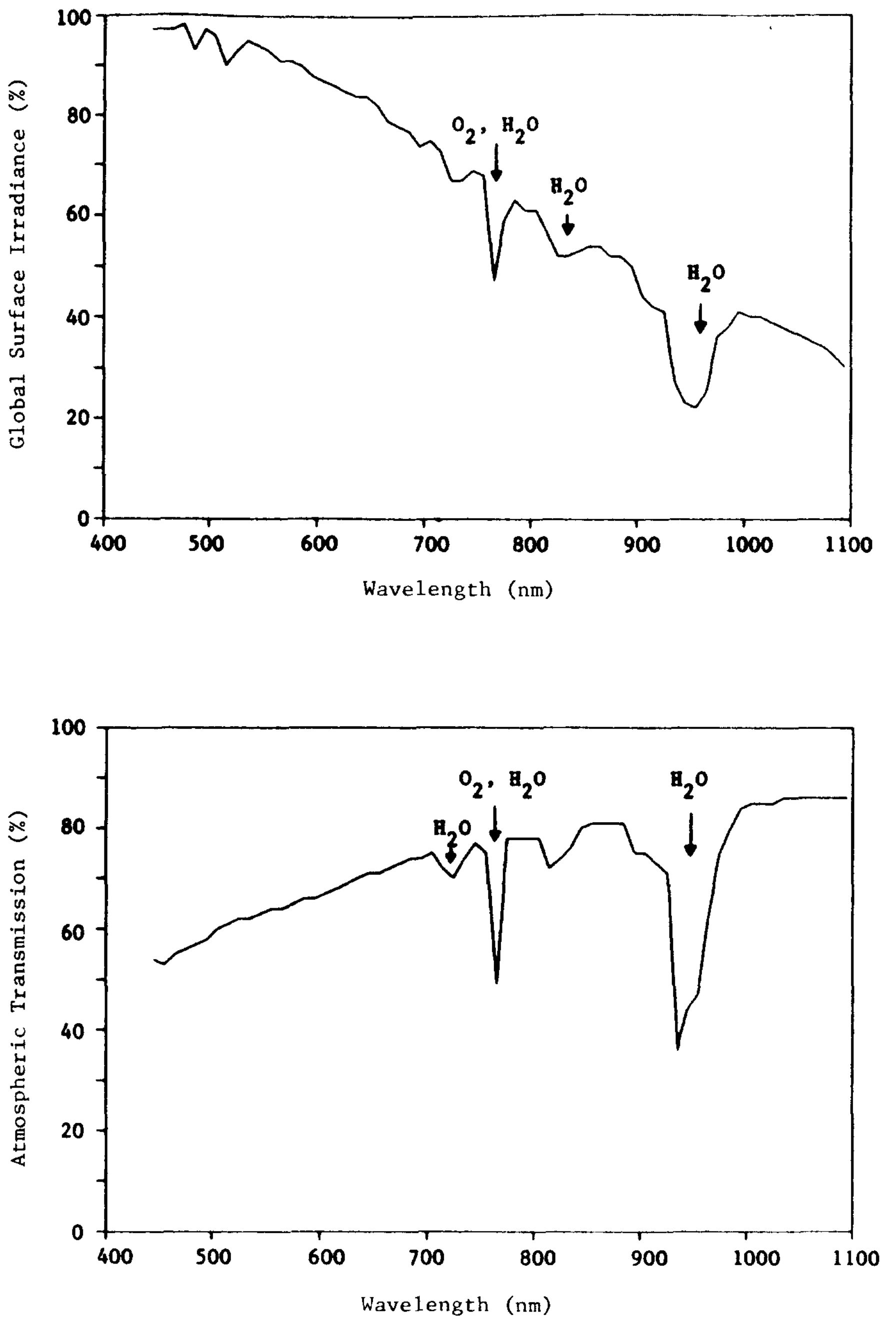

FIGURE 1. Relative global solar irradiance (top) and atmospheric transmissivity (bottom) utilized in the computation of the simulated satellite system observations.

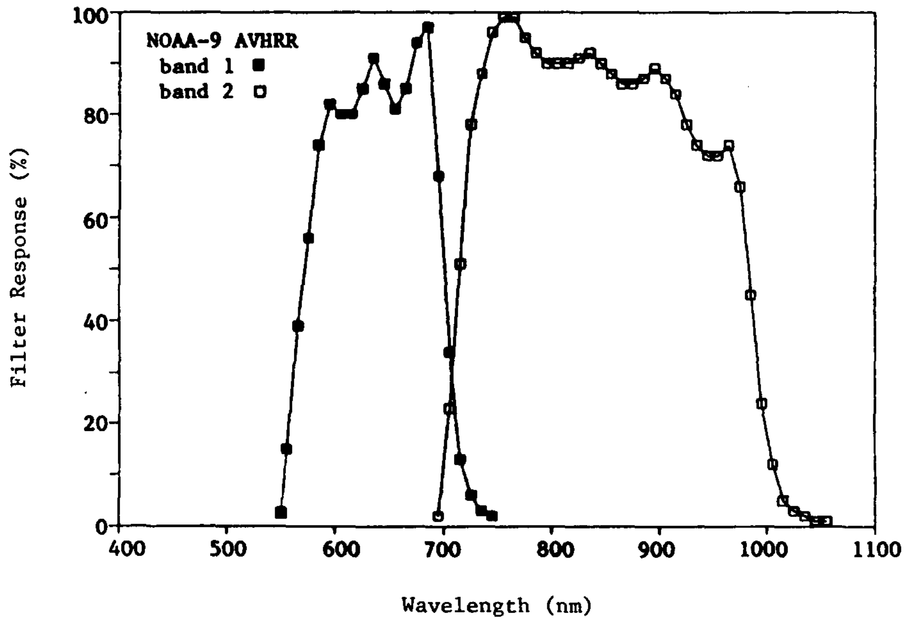

FIGURE 2. Relative filter response for Bands 1 and 2 of the NOAA-9 AVHRR.

Vegetation index variability

Greater variability in the maximum and minimum values of the vegetation indices, computed for the 2 years of the study, was observed in the simulated satellite compared to ground observation data (Table 2). The variability, as defined in Table 2, within the maximum observed RATIO and ND values was greater between the ground and simulated satellite observations than the variability in the minimum index values. The ND displayed greater variability between the minimum values of the examined sensor systems, for both the ground and simulated satellite observations, than between the maximum values. The RATIO, however, displayed greater variability in the maximum vegetation index values of the examined sensor systems than between minimum. The minimum index values for all four sensor systems were from the same observations of reflectance factor data. Differences between the sensor systems were due either to the included wavebands (ground observation) or wavebands and filter response (simulated satellite observations). The maximum values were also computed from the same observations of reflectance factor data.

The greater variability in maximum values of the RATIO compared to ND could be explained by the relationships between these indices and the agronomic variables. Similarity between the RATIO and ND indices has been demonstrated (Perry and Lautenschlager, 1984); however, the relationship between LAI and these indices is distinctly different. The maximum values of both the RATIO and ND are positively associated with the presence of green vegetation (e.g., LAI). The ND index has been observed to reach a plateau at large LAI values (Asrar et al., 1984) while the RATIO continues to

TABLE 2 Ranges and Variability in RATIO and ND Values for 1978 and 1979 Ground and Simulated Satellite Data ($n = 274$)

Sensor System	Ground Min	Ground Max	Satellite Min	Satellite Max
		Normalized Difference		
MSS	0.294	0.899	0.014	0.829
AVHRR	0.295	0.899	0.077	0.820
SPOT	0.245	0.913	0.130	0.890
TM	0.221	0.913	0.136	0.886
Variability (%)[a]	10.7	2.0	13.9	8.0
		Ratio		
MSS	1.84	18.74	1.03	10.68
AVHRR	1.84	18.78	1.17	10.14
SPOT	1.65	22.0	1.30	17.12
TM	1.57	22.05	1.31	16.62
Variability (%)	1.3	16.2	1.7	43.4

[a] Variability (%) = 100 (maximum value − minimum value)/range of all values, e.g., the range of values for the ground observations of ND is (0.913 − 0.221 = 0.692), variability within the minimum ND values is 100 (0.295 − 0.221)/0.692 = 10.7%.

increase with greater amounts of LAI (Hinzman et al., 1986). The low variability between the sensor systems at high values of ND compared to the RATIO is likely associated with the plateau exhibited in the relationship between LAI and ND.

The TM bands provided the greatest range in observed RATIO and ND values of the ground observations. The bands included on the MSS and SPOT systems provided the greatest range in observed ND and RATIO simulated satellite values, respectively. The greater range within these indices may be an indication of the sensitivity of the bands of the various sensors to the observed scene.

The variability, for both vegetation indices, among the sensor systems over a growing season could increase the difficulty of any effort to interpret relationships between agronomic variables and the vegetation indices. Seasonal variability in vegetation indices among the sensor systems was examined for the simulated satellite data obtained from canopies with two different levels (0 and 202 kg/ha) of applied *N* fertilizer. The differences in applied *N* resulted in measurable differences between agronomic variables of the canopies. The canopies that received no *N* displayed maximum values for LAI, ND, and RATIO of 3.4, 0.80, and 9.1, respectively. The canopies that received 202 kg/ha of *N* displayed maximum values for LAI, ND, and RATIO of 4.4, 0.86, and 13.5, respectively. Variability (as defined in Table 2) between the vegetation indices of the four sensor systems changed little during the growing season for ND and was greater midway through development for the RATIO (Fig. 3). Thus, the ND may be the preferable index for comparing data obtained with varied wavebands or sensors. The increased variability in the indices for the RATIO midway through canopy development can be attributed to the presence of maximum amounts of green plant matter at

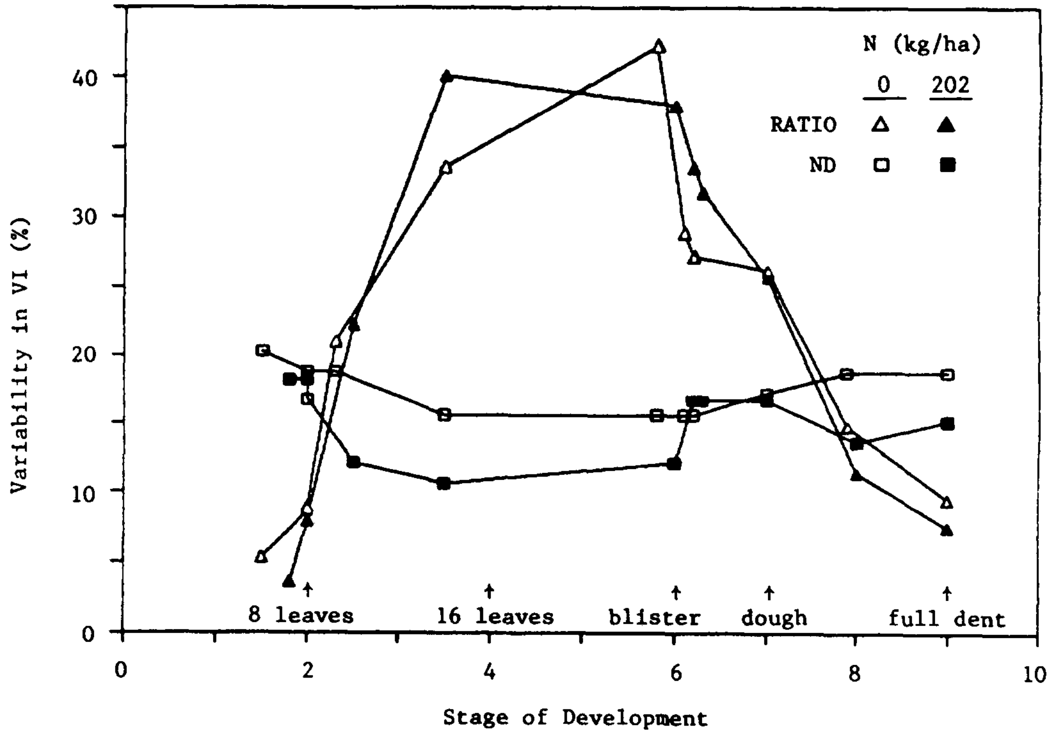

FIGURE 3. Seasonal variability between the vegetation indices (VI) of the AVHRR, MSS, SPOT, and TM sensor systems for two application rates of *N* fertilizer. Variability (%) = 100 (maximum − minimum index value among the four sensors at the specified development stage)/seasonal range of index values observed within a specific treatment.

this time (maximum LAI and percent crop cover (PCC) are observed at this time). The lack of a plateau in the relationship between LAI and the RATIO, compared to ND, would likely contribute to the greater variation in the RATIO compared to ND vegetation indices during the presence of maximum amounts of LAI. The canopies with no *N* application displayed slightly greater variation for both the ND and RATIO compared to the canopies that received an *N* application. The greater variation in the indices of the no *N* treatment may be due to the greater variation one would expect in the agronomic variables (e.g., LAI, PCC) of *N*-deprived canopies compared to canopies that received *N*.

Agronomic and vegetation index relationships

The RATIO and ND of the MSS, SPOT, and TM sensor systems were linearly related to those of the AVHRR system (Table 3). Although the intercept and slope values were often near 0.0 and 1.0, respectively, the small variations in the relationships resulted in significant differences when tests were conducted.

Linear relationships between the vegetation indices of the MSS, SPOT, and TM and those of AVHRR were, based on their coefficients of determination compared to those of quadratic equations, judged satisfactory for comparison of the sensor systems. The coefficients of

TABLE 3 Coefficients for Linear Relationships Developed between the VI of the Identified Sensor System (Dependent Variable) and the VI of the AVHRR System (Independent Variable); $n = 134$[a]

Sensor System	Regression Coefficients and Statistics			
	b_0	b_1	r^2	RMSE
Ground Observations				
		Normalized Difference		
MSS	−0.002**[†]	1.002**	> 0.999	0.001
SPOT	−0.084**	1.117**	0.999	0.006
TM	−0.130**	1.172**	0.998	0.007
		Ratio		
MSS	−0.017	1.000	> 0.999	0.05
SPOT	−0.786**	1.163**	0.999	0.15
TM	−0.972**	1.175**	0.998	0.20
Simulated Satellite Observations				
		Normalized Difference		
MSS	−0.072**	1.099**	> 0.999	0.004
SPOT	0.080**	1.006	0.998	0.008
TM	0.084**	0.999	0.998	0.008
		Ratio		
MSS	−0.307**	1.053**	> 0.999	0.06
SPOT	−1.002**	1.656**	0.998	0.16
TM	−0.957**	1.644**	0.998	0.14

[a]Only data of 1978 were included in the developed relationships. Tests were based on the assumptions that $b_0 = 0.0$ and $b_1 = 1.0$.

[†]* and ** indicate significance at the 0.05 and 0.01 levels of probability, respectively.

determination and square root of the mean square errors (RMSE) for the linear relationships developed between the agronomic variables and the vegetation indices were similar for the ground and simulated satellite observations (Table 4). Logarithmic transformations of the RATIO were the best predictors of leaf area index (LAI, Fig. 4), the green leaf biomass (GBIO), and total water content (TWC) while ND was the best predictor of absorbed photosynthetically active radiation (APAR), percent crop cover (PCC) and the total above ground fresh biomass (FBIO).

The slopes and intercepts of predicted agronomic variables of 1979 were compared to assess the developed relationships between the vegetation indices of the MSS, SPOT, and TM systems and those of AVHRR. No significant differences were detected between the slope and intercepts of the agronomic variables predicted with vegetation indices of the MSS system and agronomic variables predicted with AVHRR estimates of the MSS indices (Table 5). Differences in either the slope or intercept of these relationships were observed for several of the agronomic variables for the ground and simulated satellite observations of the SPOT and TM vegetation indices. These results indicate that vegetation indices computed from the AVHRR wavebands could be used to estimate vegetation indices of the MSS, and subsequently

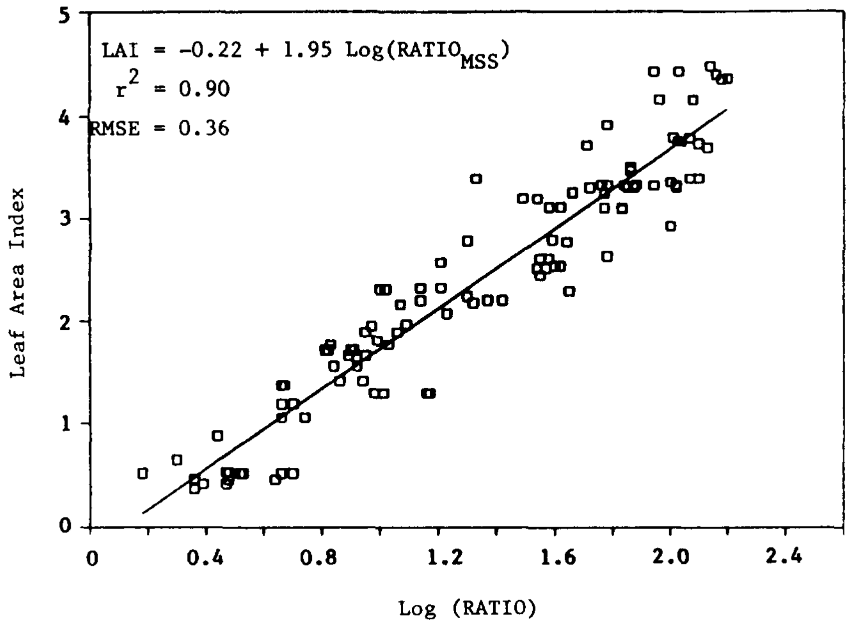

FIGURE 4. Relationship between LAI and the natural logarithm of the near-IR to red ratio for the simulated satellite data of the MSS sensor system. The fitted regression line is for the data of 1978 ($n = 109$).

TABLE 4 Predictor Variables, Coefficients of Determination, and Square Root of the Mean Square Errors (RMSE) for Relationships Developed from 1978 Agronomic Data and Vegetation Indices of the AVHRR, MSS, SPOT, and TM Sensor Systems

			MSS		SPOT		TM		AVHRR	
Variable	n	Predictor	r^2	RMSE	r^2	RMSE	r^2	RMSE	r^2	RMSE
			Ground Observations							
LAI[a]	109	log(RATIO)	0.90	0.36	0.90	0.36	0.90	0.36	0.90	0.36
APAR	109	ND	0.90	0.06	0.91	0.06	0.91	0.06	0.90	0.06
PCC	120	ND	0.64	15.1	0.64	15.0	0.64	15.1	0.64	15.0
FBIO	107	ND^2	0.69	1.19	0.68	1.20	0.68	1.20	0.69	1.19
GBIO	109	log(RATIO)	0.83	0.03	0.83	0.03	0.83	0.03	0.83	0.03
TWC	107	log(RATIO)	0.78	0.79	0.77	0.80	0.77	0.80	0.78	0.79
			Simulated Satellite Observations							
LAI	109	log(RATIO)	0.90	0.36	0.90	0.36	0.90	0.36	0.90	0.36
APAR	109	ND	0.90	0.07	0.91	0.06	0.91	0.06	0.90	0.06
PCC	120	ND	0.64	15.2	0.63	15.2	0.64	15.1	0.63	15.2
FBIO	107	exp(ND)	0.69	1.19	0.68	1.21	0.68	1.20	0.69	1.19
GBIO	109	log(RATIO)	0.83	0.03	0.83	0.03	0.83	0.03	0.83	0.03
TWC	107	log(RATIO)	0.78	0.79	0.77	0.80	0.77	0.80	0.78	0.79

[a]LAI = leaf area index, APAR = absorbed, photosynthetically active radiation (%), PCC = percent crop cover (%), FBIO = total above ground fresh biomass (kg/m^2), GBIO = green leaf biomass (kg/m^2), TWC = total water content (kg/m^2).

TABLE 5 Comparisons of Intercepts (b_0) and Slopes (b_1) of Linear Regressions of Predicted Agronomic Variables in 1979[a]

Agronomic Variables	Sensor System					
	MSS		SPOT		TM	
	b_0	b_1	b_0	b_1	b_0	b_1
			Ground Observations			
LAI	ns[†]	ns	ns	ns	ns	ns
APAR	ns	ns	**	*	**	**
PCC	ns	ns	ns	*	ns	ns
FBIO	ns	ns	**	ns	**	**
GBIO	ns	ns	ns	ns	ns	ns
TWC	ns	ns	ns	ns	*	ns
			Simulated Satellite Observations			
LAI	ns	ns	ns	**	ns	ns
APAR	ns	ns	ns	ns	**	*
PCC	ns	ns	**	**	**	**
FBIO	ns	ns	**	**	**	**
GBIO	ns	ns	ns	**	ns	*
TWC	ns	ns	ns	*	ns	ns

[a] Tests were based on the assumptions that $b_0 = 0.0$ and $b_1 = 1.0$.
[†] ns, *, and ** indicate nonsignificance and significance at the 0.05 and 0.01 levels of probability, respectively.

agronomic variables, as effectively as direct estimation with the MSS indices for otherwise similar conditions of scene observation. The AVHRR indices are linearly related to those of the SPOT and TM wavebands, however, this analysis indicates that the AVHRR indices did not estimate the indices of these systems as well they estimated the MSS indices. This result is most likely due to the similarity between the band widths of the AVHRR and MSS systems (Table 1).

Conclusions and Recommendations

The results of this study indicate that greater variability exists within the minimum and maximum values of the vegetation indices for simulated satellite, compared to ground-based, observations of relative surface radiance. The minimum ND values of the sensor systems displayed greater variability among the sensors than the minimum values of the RATIO index. The maximum RATIO values of the sensors, however, displayed greater variability between the sensors than did the maximum values of the ND index. Variability in the RATIO between the four sensor systems was greatest during middle stages of canopy development, when maximum amounts of green vegetation were present. Variability in ND for the four sensors was considerably less than for the RATIO and nearly constant for most of the growing season. Comparisons of predicted agronomic variables indicated that AVHRR data can estimate both of the vegetation indices of the MSS, and subsequently, agronomic variables as effectively as direct use of the vegetation indices of the MSS. The vegetation indices of all four systems were associated with similar amounts of variation on the examined agronomic variables.

In summary, while this analysis did include estimates of solar irradiance and atmospheric transmittance, sensor filter response and canopy reflectance at wavelengths included in computation of vegetation indices, there were several sensor and scene related characteristics that were excluded in an effort to isolate and examine only the effects waveband selection. The excluded characteristics that differ between the satellite systems include pixel resolution at nadir, sensor viewing angles, and time of sensor overpass. These differences could influence many factors that contribute to the radiance measured by a sensor located in space; e.g., scene bidirectional reflectance, path radiance, and for off nadir views, forward or backwards scatter of atmospheric radiation. These sensor system characteristics may individually, or in some combination, result in greater variation between vegetation indices of the sensor systems than those that resulted from waveband differences. Recommendations for future studies include continued assessment of the effects of these other characteristics of sensor systems on vegetation indices in isolated and combined analyses that include the system differences addressed in this study. A finer spectral scale of analysis than the 10 nm intervals utilized in this study may also be appropriate for future studies. Direct comparison of actual satellite data from observations made of a similar scene at near similar times of observation is also recommended.

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